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Using the fuzzy linear regression method to benchmark the energy efficiency of commercial buildings

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A R T I C L E I N F O

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A B S T R A C T

Benchmarking systems from a sample of reference buildings need to be developed to conduct benchmarking processes for the energy efficiency of commercial buildings. However, not all benchmarking systems can be adopted by public users (i.e., other non-reference building owners) because of the different methods in developing such systems.

An approach for benchmarking the energy efficiency of commercial buildings using statistical regression analysis to normalize other factors, such as management performance, was developed in a previous work. However, the field data given by experts can be regarded as a distribution of possibility. Thus, the previous work may not be adequate to handle such fuzzy input–output data. Consequently, a number of fuzzy structures cannot be fully captured by statistical regression analysis. This present paper proposes the use of fuzzy linear regression analysis to develop a benchmarking process, the resulting model of which can be used by public users. An illustrative example is given as well.

1. Introduction

In 2010, the Hong Kong government conducted a public consultation and consequently proposed the target of reducing Hong Kong's carbon intensity (CO_2/GDP) in 2020 by 50–60%. The Chinese government announced that the target for CO_2 emission reduction per unit GDP in 2020 would be 40–45% compared with that in 2005. Moreover, in response to the increasing amount of end-use energy consumption, the Hong Kong government pledged an international commitment to reduce energy intensity by at least 25% by 2030, with 2005 as the base year, in a joint effort to address climate change through a reduction in energy intensity in Hong Kong.

Currently, approximately 90% of the electricity consumed in Hong Kong is used in buildings [1]. Power generation accounts for almost 60% of the greenhouse gas emission, according to [2] and [3], and electricity intensity (kWh/m^2/year) increases at an annual rate of 2.3% since 1996. Therefore, electricity must be used efficiently and wisely in the future, and the means to build energy efficiency must be improved as well.

Other cities, such as Hong Kong, are facing the same challenge. Thus, benchmarking building energy efficiency is used to promote the efficient use of energy. As mentioned in [4], to conduct the benchmarking processes, benchmarking systems (or simulation models) from a sample of reference buildings must be developed to obtain "similar buildings". The benchmarking system should consider several factors because the differences in a building's energy efficiency may be affected by

- random factors, such as unusual weather conditions;
- physical characteristics, including age, number of floors, and so on;
- incentives faced by building management or the owners; and
- differences in how the building occupants utilize end-use devices.

The actual energy use performances of the reference buildings should be normalized considering the abovementioned factors. The reference buildings can then be ranked according to their energy use performance using the normalized results.

Benchmarking systems function as a public yardstick for energy use performance of the reference and other buildings. Some regulators may release benchmarking information to the media. This practice proves to be advantageous because owners/developers are needed to face with public pressure to act on poorly performing buildings. Benchmarking results can then be used to encourage poor performers (in energy efficiency) to improve their performance. Performance indicators, such as "kWh/ft^2/year" or "MJ/m^2/year", provide information that makes building users, owners, management teams, or whoever pays the utility bills accountable for their energy use performance. Moreover, a comprehensive benchmarking system can promote competition in energy efficiency by providing information on the reasons for poor

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Nomenclature

Abbreviation

SRA	simple regression analysis
SFA	stochastic frontier analysis
DEA	data envelopment analysis
QP	quadratic programming

Symbols

Y	simple adjusted performance (MJ/m^2/year)
x	factors affecting performance
$\bar{x}_i$	sample average of factor x_i
s_i	sample standard deviation of factor x_i
x_i^*	standardized form of x_i
MJ	mega joules
Y_{norm}	normalized performance
Y_o	observed performance
A_i	interval coefficient of fuzzy regression

Subscript

m	sample size
n, p	number of factor x

performance to building users or owners. A building's energy use performance can be assessed relative to reference buildings or to its past performance.

However, the different methods used to develop benchmarking systems do not allow public users (i.e., other non-reference building owners) to use all benchmarking systems. On the other hand, the present paper is partially motivated by and is based on a previous research [5]. In this previous work, a benchmarking energy efficiency model for commercial buildings by statistical analysis was developed. In the development process, data (or scores) on occupant behavior and maintenance condition, which is a subjective rating score with a fuzzy nature, were collected. However, the previous work may not be adequate to handle such fuzzy input–output data. Consequently, some fuzzy structures cannot be fully captured by statistical regression analysis. In summary, the following are the challenges:

1.1. Existing techniques are not suitable for a fuzzy environment

From the literature, simple regression (SRA), stochastic frontier (SFA), and data envelopment analyses (DEA) were commonly used for benchmarking processes [4]. However, these approaches are incapable of dealing with fuzzy variables and/or parameters. In some comparative efficiency analyses, input and output data of buildings being evaluated are often fuzzy. Hence, a number of studies, such as that of Guo et al. [6], proposed the fuzzy DEA approach to deal with the efficiency analysis problem, given fuzzy input and output data.

1.2. Existing fuzzy benchmarking methods cannot be used repeatedly

A drawback of the fuzzy DEA is the feasibility of the established benchmarking model for public users. For instance, after developing the benchmarking model for commercial buildings from a group of reference commercial buildings, other owners of such buildings (public users) cannot use this benchmarking model directly [4]. It is because that these public users are required to have all the details of the reference buildings, as well as a linear programming solver, to solve the corresponding linear programming model and to obtain the efficiency score.

A regression-based benchmarking model is one of the possible methods by which to resolve this drawback because new users can easily use the established model to obtain a benchmarking score. However, an approach to develop regression-based benchmarking models, which can be used by public users, under a fuzzy environment is currently unavailable.

This current paper presents an approach by which a benchmarking model can be developed through the application of fuzzy linear regression. The following sections are used to

- present the development of regression-based benchmarking models,
- describe the fuzzy linear regression method used in the present study,
- discuss how to build benchmarking models under a fuzzy environment,
- provide an illustrative example, and
- draw a conclusion with a few remarks.

2. The statistical regression-based benchmarking models

Generally, the following steps are undertaken to develop regression-based benchmarking models after the collection of data from a set of reference buildings (see [4,5]). First, a simple adjustment of the observed performance, e.g., climate adjustment of energy efficiency by degree-day normalization, is conducted. Second, the regression model is built to determine the relationship between the adjusted performance and the selected significant factors, e.g., climate-adjusted energy efficiency and a number of other significant factors corresponding to building characteristics. Third, the adjusted performance for the significant factors is normalized to form a benchmark table. For instance, the climate-adjusted energy efficiency for the significant factors corresponding to building characteristics is normalized to form a building energy efficiency benchmark table.

Other buildings, aside from the reference buildings, can use the benchmark table to determine their ranking and performance. Hence, such a benchmark table can be considered a yardstick for non-reference buildings. Details of regression model with standardized factors and normalization are given in the following sections.

2.1. Regression model with standardized factors

To build a regression model for the performance of buildings with a data set of sample size m, let Y be a simple adjusted performance and $x_1,\ldots, x_p$ be a set of examined significant factors. For example, Y can be climate-adjusted energy efficiency and $x_1,\ldots, x_p$ can be building age, energy system, and floor area, among others.

To normalize the significant factors to the adjusted performance, these factors are transformed from the basic set (measurements) if necessary. The base level (normal or mean standard) of each factor is determined either from the population or from the observed sample. Base levels are used as references that reflect the "normal" operating conditions (for example, the mean temperature setting for air-conditioning in an office building) and mean characteristics of reference buildings. One of the possible standardized forms is $x_i^* = \frac{x_i - \bar{x}_i}{s_i}$ for $i = 1, \ldots, p$ where $\bar{x}_i$ and s_i are the sample